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Characterization of a High-Gain Ne-like Fe Transient X-Ray Laser

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ABSTRACT

We present experimental results of a high efficiency Ne-like Fe transient collisional excitation x-ray laser using the COMET 15 TW table-top laser system at LLNL. The plasma formation, ionization and collisional excitation of the x-ray laser have been optimized using two sequential laser pulses: a plasma formation beam with 5 J energy of 600 ps duration and a pump beam with 5 J energy of 1.2 ps duration. Since the observation of strong lasing on the 255 Å 3p-3s J=0-1 transition of Ne-like Fe, we have achieved high gains of 35 cm⁻¹ and saturation of the x-ray laser. A five-stage traveling wave excitation enhances the strongest Fe 3p-3s 255 Å lasing line as well as additional x-ray lines. A careful characterization of the plasma column conditions using L-shell spectroscopy indicates the degree of ionization along the line focus.

Keywords: X-ray Lasers, transient collisional excitation, L-shell spectroscopy

1. INTRODUCTION

The transient collisional excitation (TCE) x-ray laser scheme was first proposed by Afanasiev and Shlyaptsev¹. This scheme relies on a fast pumping source comparable in time with the relaxation time scales of the excited levels. Transient collisional excitation has been demonstrated by the use of a system of two sequential pulses of laser irradiation^{2,3}. Using this method it is possible to achieve high gain and high efficiency in Ne-like and Ni-like ion x-ray lasers. The TCE creates a transient population inversion, which is pumped directly from the ground state. Over a short time, collisions redistribute the populations among all levels finally achieving quasi-steady state. Yet during this time of redistribution a short lived inversion on the time of femtoseconds to several picoseconds is created, high gain is achieved, and x-ray lasing can take place.

The first TCE x-ray laser was demonstrated by P.V. Nickles *et al*.⁴. Two sequential stages of laser irradiation were used to first preform a plasma and then second to pump the plasma to x-ray lasing conditions. The first laser pulse preforms the plasma. The needed ionization is achieved. However, the plasma is relatively cool and the needed electron temperature to collisionally populate the upper laser level is not reached. The second short pulse is delayed to optimize the conditions within the plasma for maximum amplification. The short pulse, on the order of 1 ps, is used to rapidly heat the plasma creating an electron temperature greater than the upper-laser level excitation energy⁵. In this way a transient inversion can be created and high gain conditions achieved. However, high gain lasts only for several picoseconds and decay as a result of collisional redistribution of the electron population among all excited levels, ionization, and plasma cooling.

In the following section we describe the experimental setup at the COMET laser facility at LLNL and present preliminary experimental results and analysis on the Ne-like Fe TCE x-ray laser using a 5-step traveling wave excitation. The next

section discusses L-shell spectroscopy and results are shown investigating the plasma column conditions and following this section we summarize our results.

2. EXPERIMENTAL RESULTS

The Ne-like Fe experiments were performed on the LLNL COMET laser⁶. The COMET laser can simultaneously deliver on target a long 600 ps pre-pulse beam and a high power short, 1 ps, short pulse. The energies in both beams are 5 J with each beam having a line focus of approximately 11 mm length. The intensity of the initial plasma formation beam is 7×10^{11} W/cm² and it is defocused along the direction of laser propagation. The short pulse, which is used to drive the transient collisional excitation x-ray laser, has an intensity of 5×10^{14} W/cm². A traveling wave optic was setup, which made use of a 5-step mirror. This broke the wavefront into 5 sections each with a temporal delay of 7.7 ps between steps. This gives an overall delay that corresponds to c .

The experiments with the COMET laser facility were performed using a Fe target in order to drive inversion on the Ne-like ion 3p-3s J=0-1 transition at 255 Å. Slab targets up to 10 mm in length were irradiated with a 4.8 J 600 ps (FWHM) plasma forming pulse and 4.8 J in a 1 ps (FWHM) excitation pulse. The arrival of the short pulse was delayed by 1.4 ns peak-to-peak relative to the long pulse.

We performed a detailed study of iron to measure the x-ray laser gain characteristics. Target lengths varying from 2 mm to 9 mm in increments of 1 mm were irradiated by the two laser pulses. Figure 1 shows a single shot spectrum from the on-axis spectrometer for a long 9 mm target. Strong lasing action on the long wavelength 3p-3s line at 254.9 Å is visible and is many orders of magnitude above any other line. The 3p-3s J=0-1 204.5 Å line and the 3d-3p J=1-1 226.5 Å line are also labeled on the plot.

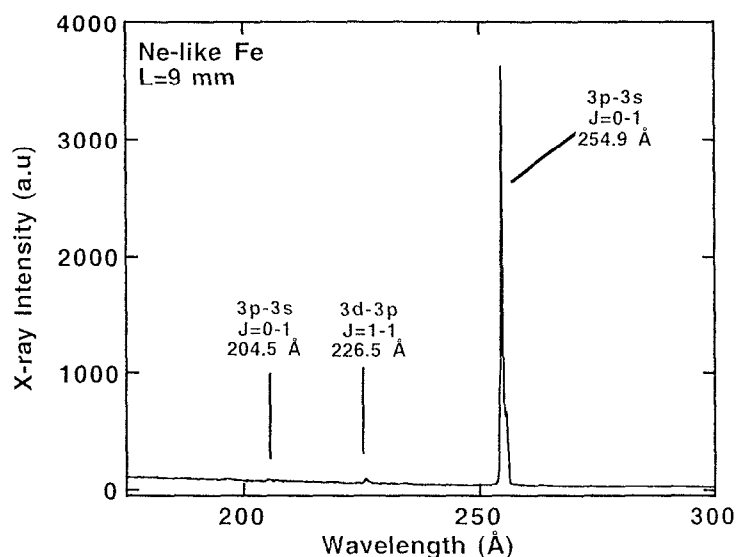


Figure 1. X-ray laser spectrum for 10 mm iron target irradiated by 4.8 J, 600 ps and 4.8 J, 1.2 ps pulses. The Ne-like 3p to 3s line at 254.9 Å dominates the spectrum.

In figure 2 the intensity versus length data is shown for the Fe 254.9 Å lasing line. The intensity curve rises exponentially up to a length of 4 mm where its growth is less exponential and approaches linear growth. Applying the Linford formula⁸ to the short target lengths 0.2-0.4 cm gives a small-signal gain of 38.2 cm⁻¹. The dashed line is to guide the eye at longer target lengths. The gain-length product (gL) is ~15.3 at 0.4 cm and is close to saturation plus a further increase of 26x intensity to 0.9 cm gives an effective gL of 18.5.

3. L-SHELL SPECTROSCOPY

In order to further characterize the plasma column conditions of the Ne-like Fe x-ray laser a high-resolution, 1-D spatially resolving spectrometer was placed at an angle of 45° normal to a 6 mm target along the line focus. Three laser configurations were considered. The first was using only the long, 600 ps 4.8 J defocused pulse. The second configuration corresponds to the x-ray laser setup in which both long pulse and short pulse after a 1.4 ns delay were used. The third configuration was to use the short pulse only, 1 ps FWHM and 4.8 J of energy. In figure 3 data from the three configurations are shown. Pinhole images were taken of the three laser configurations. The top pinhole image of the defocused long pulse shows the wedge shape of the image. The line out to the right shows the sensitivity of the pinhole image and the spikes in the image are a result of overlap in intensity due to the segmented 5-step traveling wave optic. These intensity hot spots, which normally would be corrected for in the alignment of the traveling wave optic, were used as fiducials for comparing the dispersed images from the spectrometer with the pinhole camera. To the right of the pinhole image is the FSSR spectrometer L-shell data showing the Ne-like 3C and 3D lines. The line out on the far right shows the intensity of the Ne-like 3C line through the center of the plasma column. The pinhole camera data is strongly filtered with 25 μm Be (for the 15 \AA wavelength region) which tends to over-emphasize the contrast in the hot spot regions for the long pulse only laser configuration where the overall x-ray emission is low. Comparison with the spectrometer lineout through the Ne-like 3C line shows the hot spots at the same position in the line focus but with an overall more uniform intensity. The spectrometer lineout gives the more accurate representation of the plasma line focus uniformity for the Ne-like ions for the long pulse only configuration.

For the long pulse and short pulse laser configuration which gives rise to the x-ray laser, the line focus x-ray images are largely defined by the strong plasma heating from the intense short pulse. The short pulse line focus width is constant along the plasma column as is indicated in the image. The pinhole and spectrometer lineouts are in close agreement.

The L-shell spectrum is shown in figure 4 for both the long pulse only, on the left, and both the long pulse followed by the short pulse, on the right hand side. The long pulse only L-shell spectra has been corrected for the film response (RAR2497 x-ray film) and filter response (3000 \AA Al + 2 μm Polypropylene). The main features are the Ne-like lines and Na-like satellites. The intensity of the x-ray lines is directly comparable with the long pulse and the short pulse data shown on the right hand side of figure 4. The energy in the long pulse laser beam is sufficient to ionize the plasma to a Ne-like ionization. The FSSR spectra for the x-ray laser, long pulse, 600 ps, 4.8 J followed by the short pulse, 1 ps, 4.8 J after a 1.4 ns delay yields both F-like and O-like ionization. The F-like lines indicate strong heating for the x-ray laser. We can see that the addition of the short pulse also increases the Ne-like line emission. Detailed hydrodynamics, atomic kinetics and ray-tracing modeling of the x-ray laser plasma conditions are under way and will be presented in the near future.

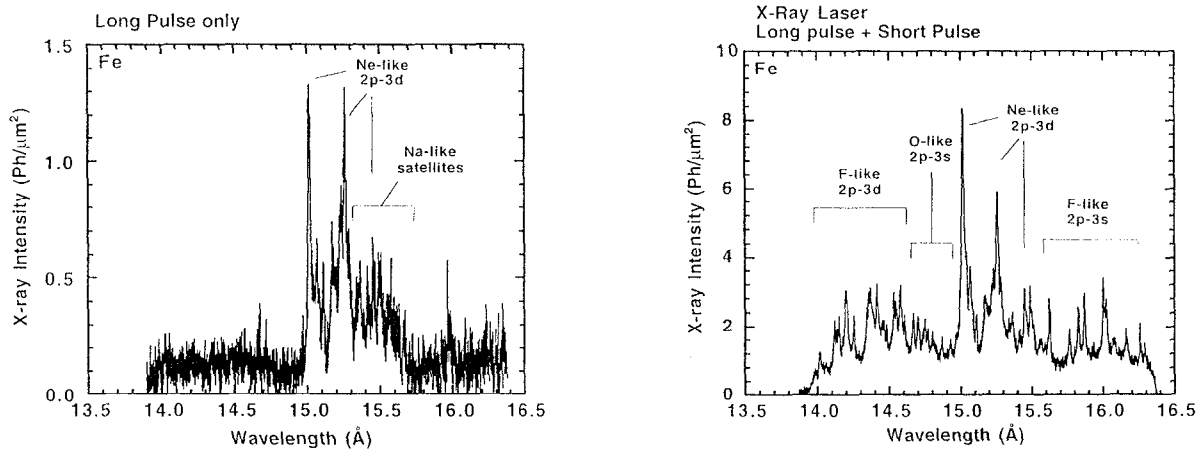


Figure 4. The FSSR spectrometer indicates the degree of ionization of the Ne-like Fe x-ray laser plasma along the line focus. Both figures show the Ne-like 3C and 3D lines. The preformed plasma's L-shell spectrum, long pulse only, shows the Ne-like lines. The plasma conditions for the x-ray laser show both F-like and O-like ions.

4. SUMMARY

At the COMET laser facility we have demonstrated high gains of 38.2 cm^{-1} and achieved saturation for the Ne-like Fe 3p to 3s $J = 0$ to 1 transient collisional excitation x-ray laser at 254.9 \AA . The usefulness of traveling wave pumping has been demonstrated. Results from L-shell spectroscopy show that the long plasma preforming pulse achieves Ne-like ionization

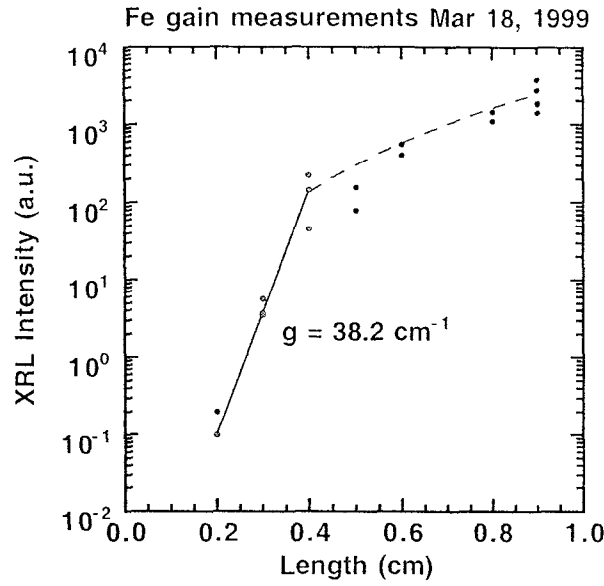


Figure 2. Intensity versus length plot for the Ne-like Fe 3p to 3s $J = 0$ to 1 x-ray laser at 254.9 Å. Small-signal gains $\sim 38.2 \text{ cm}^{-1}$ are determined for short target lengths up to 4 mm.

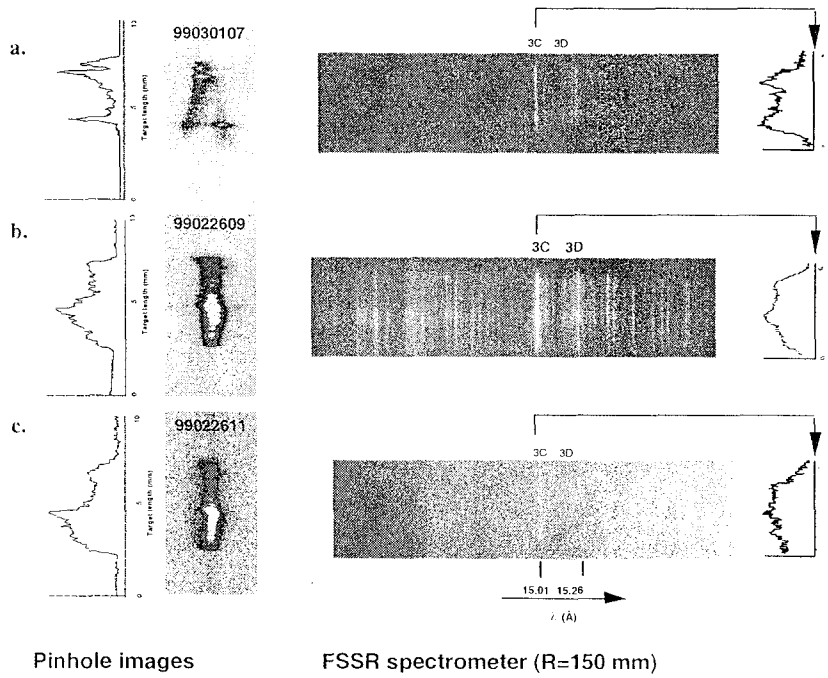


Figure 3. L-shell spectroscopy allows us to characterize the plasma column conditions of Ne-like Fe x-ray laser. The pinhole images and the FSSR spectrometer are shown for three laser parameters incident on a 6 mm long target. The image a. is with the long pulse only and the pinhole image shows the effect of the defocusing. The second image, b., is the x-ray laser setup where the long pulse is followed by the short pulse after a 1.4 ns delay. The third image, c., is using the short pulse only. The lineouts are the intensity along the center of the line focus.

levels. The x-ray laser plasma, with the combination of both long pulse and short pulse, reaches ionization levels of F-like and O-like Fe.

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